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Rare Decays of the Z-Boson

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Abstract

We study radiative decay modes of the Z-boson into heavy quark bound states. We find that the widths for these decays are extremely small. We conclude that these decays will not be detectable for the time being unless there is a significant increase in the number of Z-bosons produced at the electron- positron colliders.

Rare decays of the Z-boson have recently been studied at the e^+e^- colliders, CERN's LEP and the SLAC Linear Collider, where branching ratios down to 10^{-6} corresponding to a few Kev can be measured ^[1]. The partial decay widths of the Z-boson to a photon and bound states of heavy quarks (J/ψ) have been previously calculated by using Bethe-Salpeter wavefunctions for the quarkonium state and model-dependent potentials and found to be about .2 Kev ^[2] which might be observable soon. However, using a model-independent method, we show that these decay widths are actually much smaller than previously reported.

Calculation of the amplitudes $A(Z \rightarrow J/\psi\gamma)$ and $A(Z \rightarrow \Upsilon\gamma)$

We are considering the decays $Z \rightarrow J/\psi\gamma$ and $Z \rightarrow \Upsilon\gamma$. The quark diagrams for the first decay are shown below with similar diagrams for the second case (replace c and \bar{c} by b and \bar{b}).

Fig.1. The quark diagrams for $Z \rightarrow J/\psi\gamma$ decay

Here we are assuming that the quarks inside the meson are at rest with respect to each other. In other words, we are making the approximation that $P(c) = \frac{1}{2}P(J/\psi) + O(\frac{\mu}{m_c})$, where $\mu = .5 \text{ Gev}$ is the characteristic hadronic scale here. This is not a very good approximation for the c quark, but is much better for the b quark ^[3]. Then we will have $m_{J/\psi}^2 = 4m^2$, $(P + K)^2 = M^2/2$ and $Q = 2P + K$ where m and P are the quark mass and momentum, M and Q are the Z-boson mass and momentum and K

is the photon momentum. The amplitude is given by:

$$\begin{aligned}
A(Z \rightarrow J/\psi\gamma) = & \epsilon_\mu^z \epsilon_\nu \langle J/\psi | \bar{C} \{ [(\frac{-ig}{2\cos\theta_w})\gamma^\mu (C_v - C_A\gamma^5) \\
& (\frac{i}{(\not{P} - \not{Q}) - m})(iQ_c e\gamma^\nu)] + [(iQ_c e\gamma^\nu)(\frac{i}{(\not{Q} - \not{P}) - m}) \\
& (\frac{-ig}{2\cos\theta_w})\gamma^\mu (C_v - C_A\gamma^5)] \} C | 0 \rangle
\end{aligned} \tag{1}$$

Here, ϵ_μ^z and ϵ_ν are polarization vectors of the Z -boson and photon respectively and $e^2 = 4\pi\alpha$ where $\alpha = 1/137$ is the electromagnetic coupling constant and $g = \frac{e}{\sin\theta_w}$, $Q_c = 2/3$ is the charmed quark electric charge, $C_v = T^3 - 2\sin^2\theta_w Q_c$ and $C_A = T^3$ are respectively the vector and axial vector coupling in the Weinberg-Salam theory, T^3 is equal to $\frac{1}{2}$ for a c quark and $-\frac{1}{2}$ for a b quark, $\sin^2\theta_w \simeq .23$ and $\sigma^{\mu\nu} = i/2(\gamma^\mu\gamma^\nu - \gamma^\nu\gamma^\mu)$.

Eq.(1) can be simplified, after some γ matrix algebra and using the identity $\gamma^\mu\gamma^\lambda\gamma^\nu = g^{\mu\lambda}\gamma^\nu + g^{\lambda\nu}\gamma^\mu - g^{\mu\nu}\gamma^\lambda + i\epsilon^{\sigma\mu\lambda\nu}\gamma_\sigma\gamma^5$ and the Dirac equation $\bar{U}(P)(\not{P} - m) = 0$ and $(\not{P} + m)V(P) = 0$ to,

$$\begin{aligned}
A(Z \rightarrow J/\psi\gamma) \simeq & \frac{2iQ_c e g}{3M^2 \cos\theta} \epsilon_\mu^z \epsilon_\nu \langle J/\psi | \bar{C} \{ [-2iC_v(Q_\lambda - P_\lambda)\epsilon^{\sigma\mu\lambda\nu}\gamma_\sigma\gamma^5] - \\
& [C_A(4mi\sigma^{\nu\mu}\gamma^5 - 2P^\mu\gamma^\nu\gamma^5 + 2P^\nu\gamma^\mu\gamma^5 + \\
& 2i\epsilon^{\sigma\mu\lambda\nu}Q_\lambda\gamma_\sigma)] \} C | 0 \rangle
\end{aligned} \tag{2}$$

The term involving $\sigma^{\nu\mu}\gamma^5$ is proportional to $\epsilon^{\nu\mu\lambda\sigma}\sigma_{\lambda\sigma}$ and in general, has non-zero matrix element in the above expression, but its' contribution is of the order of $\frac{m^2}{M^2}$ and here, we have neglected $\frac{m^2}{M^2}$ terms. Now, using the fact that the matrix element of a pseudo-vector taken between a vector state and vacuum state is zero, we get,

$$A(Z \rightarrow J/\psi\gamma) \simeq \frac{-4Q_c e g C_A}{3M^2 \cos\theta} \epsilon_\mu^z \epsilon_\nu \epsilon^{\sigma\mu\lambda\nu} Q_\lambda \langle J/\psi | \bar{C} \gamma_\sigma C | 0 \rangle \tag{3}$$

The matrix element of the vector current in the above equation can be written as,

$$\langle J/\psi | \bar{C} \gamma_\sigma C | 0 \rangle = 4g_v m^2 \phi_\sigma \tag{4}$$

where ϕ_σ is the polarization vector of J/ψ and g_v is experimentally found to be about .13. Now, squaring the amplitude will give us,

$$|\bar{A}(Z \rightarrow J/\psi\gamma)|^2 \simeq \frac{224\pi^2\alpha^2 Q_c^2 C_v^2 g_v^2 m^4}{\cos^2 \theta_w \sin^2 \theta_w M^2}$$

For the $(Z \rightarrow \Upsilon\gamma)$ decay, we follow the same procedure with $\langle \Upsilon | \bar{b}\gamma^\mu b | 0 \rangle = 4g'_v m_b^2 \phi^\mu$ and g'_v is found from $\Upsilon \rightarrow e^+e^-$ decay rates to be about .04 . Then,

$$|\bar{A}(Z \rightarrow \Upsilon\gamma)|^2 \simeq \frac{224\pi^2\alpha^2 Q_b^2 C_v^2 g'^2_v m_b^4}{\cos^2 \theta_w \sin^2 \theta_w M^2}$$

and for the decay rates, using $M = 91\text{Gev}$, $m_c \simeq 1.5\text{Gev}$, $m_b \simeq 4.5\text{Gev}$ and massless two-body decay phase space, we get $\Gamma(Z \rightarrow J/\psi\gamma) \sim 10^{-10}\text{Gev}$ and $\Gamma(Z \rightarrow \Upsilon\gamma) \sim 10^{-9}\text{Gev}$

To summarize, we have shown that decay widths for $Z \rightarrow J/\psi\gamma$ and $Z \rightarrow \Upsilon\gamma$ are much smaller than previously reported and unfortunately, will not be experimentally observable for the time being.

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